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Editorial

Taking a downward turn on the weight spiral – Lightweight materials in transport applications

1. Introduction

The present special issue of *Materials and Design* arranges several articles on the topic of "Lightweight Materials and Structural Solutions for Transport Applications" around a core of papers originally presented in a dedicated symposium at the Euromat 2013 conference held in Sevilla, Spain, from September 8th–13th, 2013.

All contributions originating from this event have been carefully amended and extended to the level of regular journal articles. As such, they passed the standard, thorough peer review process implemented by Materials and Design, in this case co-moderated by the guest editors, the authors of the present introduction. Furthermore, none of the contributions has been previously published in conjunction with the conference, since the Euromat series does not feature any proceedings.

Weight reduction is a permanent issue in transport applications, and thus lightweight materials, structures and associated processes are focal areas of research in this industrial sector. They are inseparable, too, because the processing route that turns materials into engineering structures will necessarily affect material properties [1]. It is commonplace knowledge that much of a component's costs are determined in early design phases, and greatly influenced by material and process selection. Thus when considering introduction of new materials, design engineers must be aware of the effect of both materials and processing on performance, manufacturability and cost. Lightweight design, which according to a much-cited statement aims to place the right material in the right place, is centered on exploiting material properties to the limit. Margins are becoming smaller here, and thus besides extending knowledge on materials and processes, a parallel development of modelling, simulation and optimization methodologies and tools becomes a necessity of similar importance. Hence, Materials and Design, which aims at linking the design and materials engineering communities, is a natural haven for a special issue on this topic.

The present editorial cannot claim to comprehensively cover the topic for all transport modes addressed. Therefore, we have decided to focus our introductory remarks on developments in the automotive industry to show that lightweight materials and structures are indeed a success story despite the many challenges they face. Furthermore, we want to highlight that changing boundary conditions and fundamental technological approaches require continued efforts in research and development to secure what has been achieved and facilitate further progress.

The weight spiral is a frequently quoted term which originates from the automotive sector and describes this industry's efforts to limit generation-to-generation vehicle weight increase despite safety requirements and customer demands for added comfort and functionality. The actual achievements of these efforts become visible when more meaningful measures than merely the vehicle weight are used to compare consecutive generations of individual car models. One concept in this respect, which takes parallel tendencies like size increase and performance improvement into account, is the so called "Leichtbaugüte" or, translated freely, lightweight design quality factor. This measure is typically calculated for the body-in-white (BIW) via dividing its weight by the product of static torsional stiffness and footprint as defined by wheelbase and track [2].

In Fig. 1, a more simplistic approach has been chosen to partly reflect generation-to-generation growth within one vehicle class via a footprint size calculated from length and width of the car. The upper left diagram compares weight increase with the parallel development of this figure as indication of vehicle size. Five size classes from supermini to luxury cars (B- to F-segment according to the European Commission classification scheme) are contrasted based on public data and using the smallest and lowest weight model variant in each case. The additional five diagrams highlight on a class-by-class level the development of the ratio between vehicle weight and footprint in recent years. The same three exemplary model lines per class are chosen for these diagrams that also form the basis of the upper left figure. Each data point, or inflection of the curve, represents a new generation of the respective vehicle model.

Not surprisingly, the diagrams reveal that on this partially size-corrected basis, lightweight design has helped to approach a saturation level in almost all size classes roughly at the start of the present millennium. The reasons behind this reversal of the weight spiral are manifold. They are helped by the same effects that have made weight increase even steeper in the past. Over several years, the main drivers for weight increase have been enhancement of safety, comfort (including size) and performance. Adding components, e. g. electric drives for seat adjustment systems, means adding weight, and such primary weight increase is coupled to several secondary effects that amplify the initial impulse: as kinetic energy of the vehicle increases, passive safety measures have to be adjusted. Similarly, if performance is to be maintained, power needs an upward shift, and powertrain weight will follow suit. Today, we see several trends that counteract these tendencies. The list below is not conclusive, but may still support our point:

- as exemplified in several cases in Fig. 1, size increase within vehicle classes has become less prominent, thus less size-based weight increase has to be compensated by secondary

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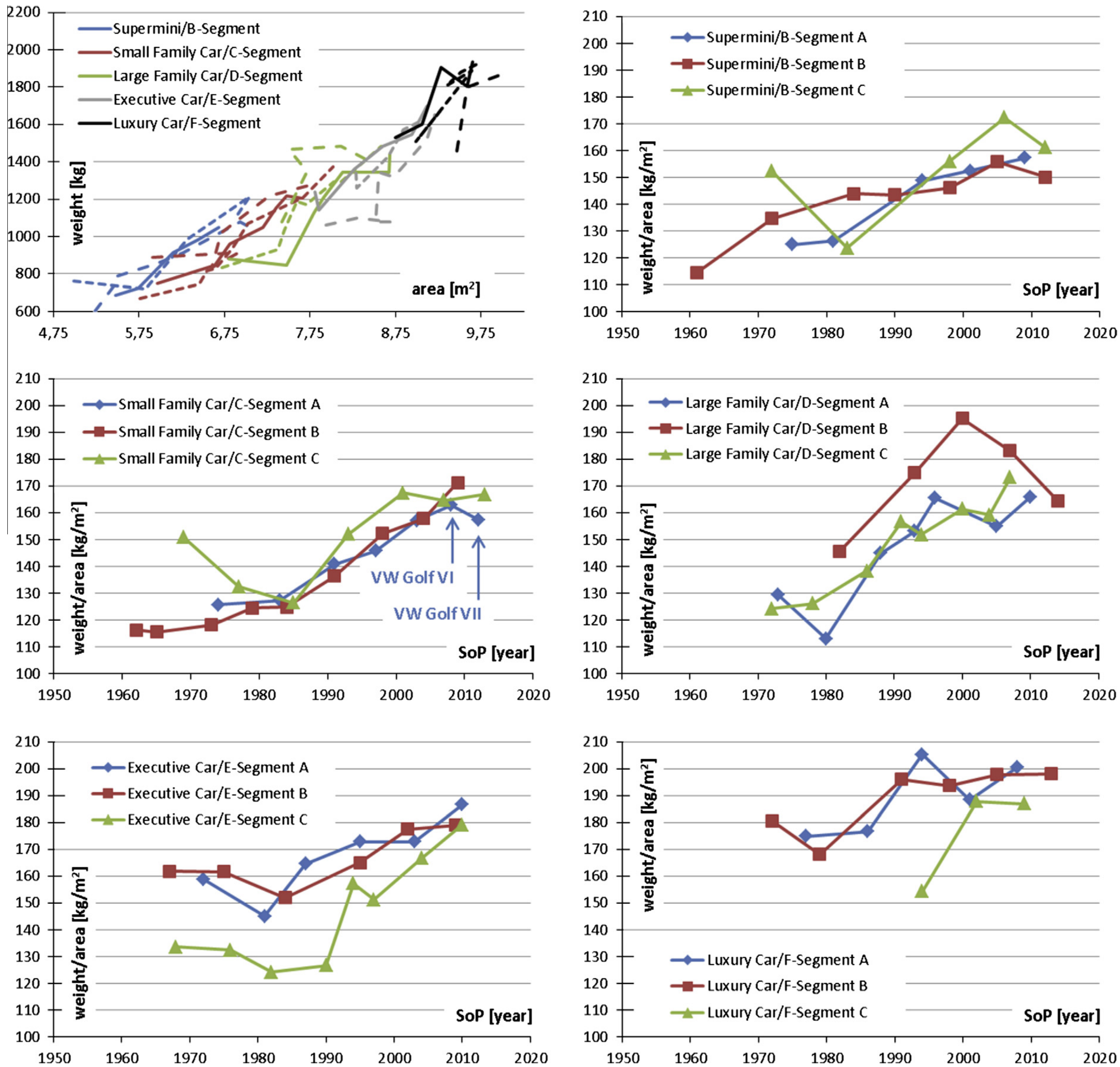

Fig. 1. Development of weight and size over vehicle generations (top left) and trends in weight per size for different vehicle classes over time. Data collected from various sources, incl. OEM public websites.

measures (e.g. engine performance, body stiffness, passive safety adaptation);

- internal combustion engine (ICE) and powertrain development has improved power to weight ratio;
- customers have come to accept the downsizing of engines;
- improvements in comfort are increasingly based on information and communication technology (ICT) solutions, which add less weight;
- safety improvements are achieved via active safety measures, too.

Such developments are enabling design engineers to actually profit from the many lessons already learned in lightweight design: whereas improvements in this field have been mandatory to open up some freedom of design in the past, they now lead to an actual weight reduction. And this reduction can trigger the same secondary effects that formerly made halting the upward trend so difficult.

One concrete example for this development is the Volkswagen Golf VI and VII. Fig. 2 reflects the distribution of weight over components and materials, respectively, for the earlier model. In accordance with the dictum of "the right material in the right place", hybrid materials and structures have often been suggested to reduce vehicle weight, and no doubt they can excel in that respect, as has been shown on a European level e. g. in the course of the "SuperlightCar"-project [4]. However, the Golf example can highlight additional access paths. The design of the Golf VI as such is mostly steel based with comparatively low proportions of light metals and composites. For the Golf VII, the overall image is not that much different. However, the new concept does make significant use of new material variants and associated processes. This is reflected e. g. in an increased application of hot forming of ultra high strength steels as well as advanced high strength steels (AHSS). But such measures, which are mainly associated with the structural framework, only make up part of the weight savings achieved in the transition from Golf VI to VII (see Fig. 1, in which the effect is highlighted). According to public Volkswagen sources, weight reductions have been realized in superstructure (−37 kg), running gear (−26 kg), engine (−12 kg), special equipment (−22 kg) and the electrical system (−3 kg) and thus adds up to 100 kg [5]. The latter two contributions hint at functional integration as further, promising path towards light vehicles. In general, polymer-based materials lend themselves easier to this approach than metals – another argument favouring hybrid design approaches.

This said, however, it must be conceded that the above observations mainly cover conventional ICE vehicles. The issue is a little different for electric vehicles. Here, the limited energy density of the battery package and its need for additional protection results in weight increases despite the fact that energy storage capacity still does not suffice to reach the range figures common to ICE vehicles.

Fig. 3 depicts the ratio between hybrid and electric variants of certain car models and their direct, ICE-based counterparts. As can be seen from this figure, the line of equality is never reached. Thus besides improvements in energy and power density of battery systems, lightweight design can make a direct contribution to rendering specifically FEVs more attractive, if e. g. a decrease in weight is translated into battery capacity.

Individual challenges for lightweight design exist in other transport modes. In the aerospace industry, the current transition from metal to carbon fibre reinforced plastic (CFRP) structures has opened up many research issues. Besides the general need for even deeper understanding of material performance e.g. in terms of fatigue, topics like process improvement for higher yield or lower cost as well as the realization of hybrid joints and structures that link FRP to metal on material and structural level can be named. Specifically in these areas, borders between transport industry sectors may easily be crossed, and the special need of lightening FEVs may serve as catalyst. This is exemplified e.g. by the large-scale introduction of CFRP structures in BMW's i3 full electric vehicle – the first introduction of CFRP as primary body material in a car of this production volume class.

Still somewhat unique to aerospace structures is the topic of sensor and electronics integration for realizing structural health monitoring of self-sensing structures [6,7]. The link to lightweight design is via a reduction of safety factors in return for the permanent awareness of structural state provided by the system.

2. This issue: Research on lightweight materials and structures

Most of the above issues found their reflection in the Euromat symposium at the basis of the present special issue, which is divided in the four thematic sections introduced below.

Modeling, simulation and optimization of materials and structures is in many ways connected to material usage in transportation structures. Existence of suitable material models and modelling techniques is a prerequisite for introducing new materials in product design. Such models and the associated simulation and optimization techniques and tools are increasingly required to include stochastic methods in order to allow e.g. robust optimization and enable virtual testing approaches. At the same time, fundamental simulation techniques like e.g. *ab initio* methods are more and more being used to tailor material properties over several length scales to specific application requirements.

The related session of the special issue is headed by a contribution by Hohe et al. on modelling the influence of uncertainties on FRP material behaviour [8], followed by Mozafari et al.'s numerical study on optimum design of a sandwich structure for railway applications [9]. The section closes with an account on the simulation-supported design of laminated metals towards increased ductility under tensile load by Cohades et al. [10].

The following section addresses Composite and hybrid materials and structures.

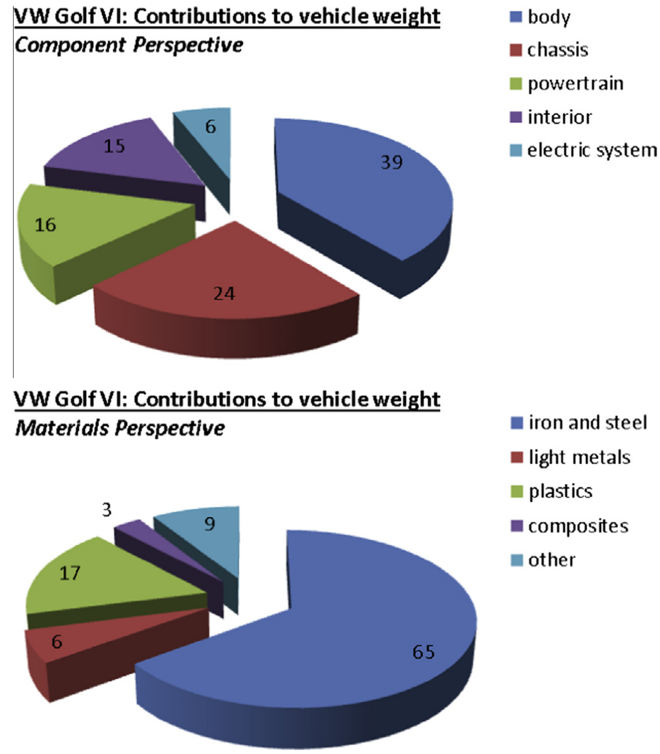

Fig. 2. Volkswagen Golf VI: contributions to vehicle weight in terms of components/functional units (top) and materials (bottom) based on Ickert et al. [3].

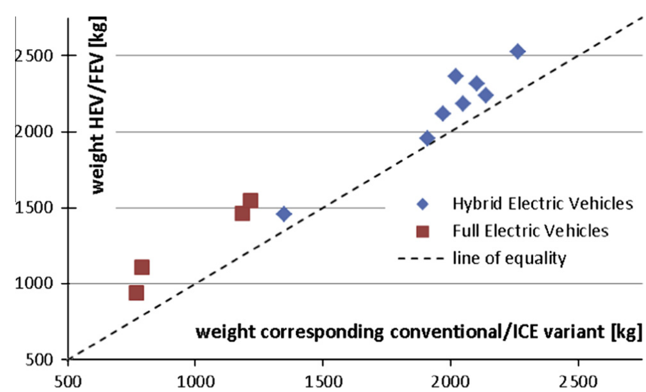

Fig. 3. Comparison in gross vehicle weight between conventional, ICE car models and corresponding hybrid electric vehicle (HEV) and full electric vehicle (FEV) variants, based on Ickert et al. [3].

Although both aerospace and automotive industries use more and more fibre-reinforced plastics (FRP), the share of metals remains significant. Hybrid concepts will see both materials combined on structural, but also on material level, e.g. in the form of fibre-metal laminates currently flying e.g. in the A380 fuselage. Besides their properties and specifically the influence of interface characteristics on them, economic production processes are the major interest today. The section has been extended beyond the strictly hybrid materials and structures (i.e. Al-FRP, Steel-FRP, etc.) by metal–metal (e.g. Al-Steel, Al-Ti) concepts as well as polymer and metal matrix composites.

In an invited contribution Rene Alderliesten first reviews the state of the art in damage-tolerant design for aerospace structures using fibre-metal-laminate (FML) technology [11]. Hasselbruch et al. discuss properties and failure of hybrid, thermoplastic matrix FRP-metal structures in a subsequent work [12]. Friction spot joining, a new technique for hybrid joints between CFRP and metals is the subject of a study by Esteves et al. [13]. Abdullah et al. look into interfacial fracture of thermoplastic composite-based FMLs [14]. Joining aluminium and galvanized steel and parameter influence on joint characteristics is the object of Shao et al.'s work [15]. A similar topic is considered by Haddadi, though his interest is concentrated on interface development during the ultrasonic spot welding process [16]. Polymer matrix composites based on natural fibres are introduced by Nassiopoulos and Njuguna [17]. Gendre et al. evaluate impact performance of polyamide 6 nanocomposites [18]. Metal matrix composites are introduced by Zhao et al. and Wang et al. [19,20].

Energy absorbing and protective materials and structures are the focus of the third section. Across the transport industry sectors, design criteria lightweight structures often include passive safety related performance characteristics. These have to be experimentally derived and translated into general principles on material and structural level, including e.g. the role of material interfaces. Besides, there is a continuing tendency towards improving the overall safety of transportation units e.g. by coverage of more accident scenarios with dedicated safety systems (e.g. vulnerable road user protection) or integration of active and passive systems. The present symposium addresses the related issues from the perspective of mechanics of materials and structures with a special focus on high strain rate/impact performance.

The two first contributions in this section provide a link to the previous, as with metal matrix syntactic foams, they are dedicated to a special type of metal matrix composite. Licitra et al. cover aluminium matrix materials, while invar matrix syntactic foams are studied by Luong et al. [21,22]. The making and mechanical performance of aluminium foam filled aluminium tubes is explained by Duarte et al. [23]. A quite different material, though also applied for energy absorption purposes, is the zeolite/water system about which Sun et al. report [24]. A mechanically stable high temperature ceramic thermal protection system is suggested by Wei et al. [25] and closes the section.

The final, fourth section of the special issue is dedicated to new developments in *Metals* technology. In the past, the advent of new materials in any field of the transport industry has always fuelled new developments among the previously dominating, now threatened ones, pushing performance to new limits across all classes of materials. Currently, initiation of new developments is very much linked to CFRP introduction, but as already the example of Golf VI and VII showed, there is still a lot to be gained by e. g. implementing the latest steel grades. Similarly, the light alloys magnesium, aluminium and titanium still have considerable development potential.

Advanced design of melt-processed magnesium alloys is treated by Paramsothy and Gupta in their paper [26], while Peng et al. study effects of homogenization on microstructure and properties of low density Mg–Li alloys [27]. Springback of Mg and thus the processing of this material is treated by Li et al. [28]. Switching to aluminium, Liao et al. report about the influence of Cu on microstructure and properties of 7000 series alloys [29]. Azadi et al. have investigated new approaches towards prediction of damage evolution in aluminium alloys [30]. Shekhar et al. have characterized the effect of solution and ageing treatments on microstructure and performance of a β titanium alloy, Ti–5Al–5V–5Mo–3Cr [31]. Superplastic behaviour of TiAl6V4 at high strain rates and low temperature is the subject of Matsumoto et al. [32], while sheet metal forming of titanium is discussed by Badr et al. [33]. Finally, closing this special issue, directionally solidified TWIP steel is studied by Wang et al. in terms of microstructure evolution and strain hardening [34].

3. Conclusion and outlook

Coming back to the automotive perspective, it is the understanding of the car as a complex system of interdependent components and functional units which explains why reversing the weight spiral proved so hard. Similarly, this interdependency is the basis of the high hopes linked to the fact that the reversal may have been achieved by now. Naturally, this does not make lightweight design obsolete. Instead, this development bears the promise that in future, lightweight design may live up to its promises even more clearly than in the past.

For transport applications, lightweight design thus is and will remain a central issue, since performance is linked to weight, irrespective of the former being measured in miles per gallon, maximum range, top speed, passenger or cargo capacity or acceleration, and irrespective also of the transport mode.

In previous years, the Euromat conference series has offered a forum to present and discuss materials engineering solutions to the challenges design engineers face in this respect. This forum we intend to expand:

Euromat 2015 will be held from September 21st–24th, 2015, in Warsaw, Poland. Many of the topics discussed at Euromat 2013 in Sevilla are planned to be taken up again in Warsaw. These include hybrid, intelligent and adaptive as well as protective materials and structures. However, we intend to add new perspectives, too, like the potential of additive manufacturing techniques for present and future transport applications.

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